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Ignition Methods for a 155-mm Regenerative Liquid Propellant Gun

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Methods are discussed for igniting a 155-mm regenerative liquid propellant gun (RLPG). A discussion is given of the igniter design requirements and the igniter concepts under consideration. The designs differ in the location in which the igniter charge is burned, the type of propellant used as the igniter charge, and the method in which the igniter charge is initiated. The igniter design concepts fall into two categories, external and internal. In an external igniter the igniter charge is burned outside the gun chamber in a precombustion chamber at a high loading density. In an internal igniter, the igniter charge is burned inside the gun combustion chamber at a lower loading density. The propellants investigated for an igniter charge include hydrogen-air mixture, fuel-air mixture, and liquid propellant, the latter being most desirable because it will be stored on the Self Propelled Howitzer (SPH). The ignition source being considered is electrical because of its availability on the SPH.

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IGNITION METHODS FOR A 155-MM REGENERATIVE INJECTION LIQUID PROPELLANT GUN

by

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and
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FEBRUARY 1988

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U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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I. INTRODUCTION

Artillery system studies, based on the 155-mm self propelled howitzer (SPH), have shown that there are potential logistical advantages of using a liquid propellant gun in place of the conventional solid propellant gun.[1] The logistical advantages of the use of liquid propellant (LP) include increases in propellant inventory, both in storage areas and on the SPH, reductions in handling and transportation throughout the supply chain, and an increase in projectile inventory on the SPH. In addition, the use of an ignition system which uses the liquid propellant as an igniter charge would further increase the advantages of the Regenerative Liquid Propellant Gun (RLPG) system.

The ignition of liquid propellants was investigated during the work done on bulk loaded liquid propellant guns (BLPGs). Most of the research focused on conventional pyrotechnic or electric spark systems, although some studies included ignition sources such as hot wires, lasers, ultrasonic devices, and chemical ignition.[2] Research was eventually directed towards the RLPG because of problems that persisted in relation to the control of ignition and combustion during the interior ballistic cycle of bulk loaded guns.

The General Electric Company began investigating the regenerative gun concept in an IR&D program in the early 1970's. Many of the RLPG fixtures tested to date have relied on an external pyrotechnic igniter. In this type igniter, the solid propellant igniter charge is burned at high pressure, external to the gun chamber, and the hot gases and burning particles are vented into the combustion chamber. An igniter of this type, used to ignite 30-mm RLPG fixtures, is shown in Figure 1. The solid propellant igniters used at General Electric have been of simple design and have consistently ignited the LP in a reproducible manner. However, there has not been a detailed igniter research effort in the development of the RLPG fixtures during the past ten years. Nor has there been an effort to optimize the igniter design in use. Instead, the goal has been to develop a simple igniter with reliable and controllable output that leads to sustained ignition of the injected liquid propellant.

The LPs currently being used in the United States are aqueous solutions of nitrate salts, with hydroxylammonium nitrate (HAN) as the oxidizer component and an aliphatic amine as the fuel component. There have been several formulations of the HAN based propellants developed in the past few years.[3] The differences in the LP's are the type and percentage of the fuel component and the percentage of water. One of the current formulations is Liquid Gun Propellant (LGP) 1845. The fuel is triethanol ammonium nitrate (TEAN). The composition of LGP 1845 (based on weight) is 20.0% TEAN, 63.2% HAN, and 16.8% water. Based on the requirements of the gun system, the HAN based liquid propellants currently hold the greatest promise for use in medium to large artillery gun.[3]

The objective of this report is to present the concepts that are being considered for an ignition system of a 155-mm RLPG.

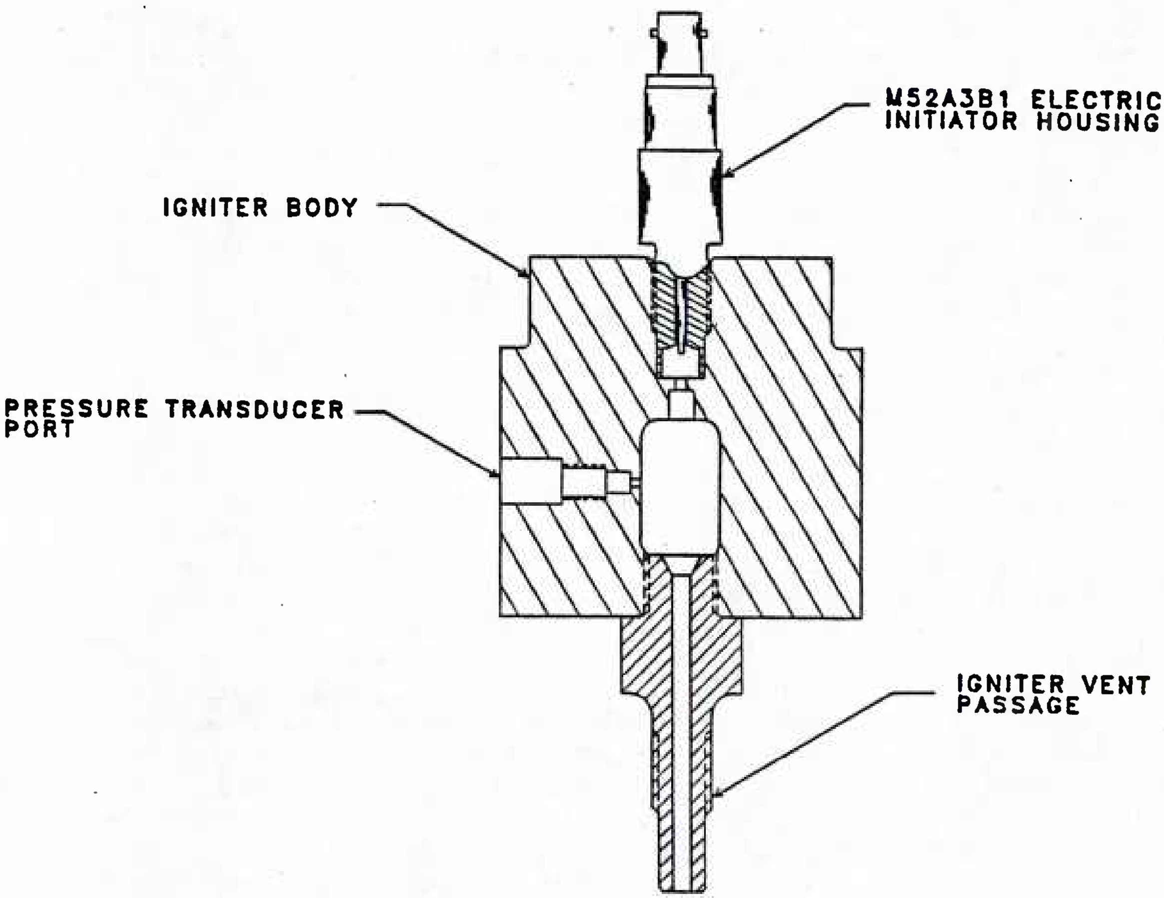

Figure 1. 30-mm RLPG Solid Propellant Igniter

II. RLPG IGNITER DESIGN REQUIREMENTS

In this section the design requirements for the ignition system of a 155-mm RLPG are presented. The reader is referred to Reference 1 for a discussion of the RLPG concept.

The design requirements are formulated from the igniter experience the General Electric Company has obtained with their medium and large caliber fixtures.[4] The GE ignition systems consist of an electrically initiated primer followed by a solid propellant igniter charge. However, it is desirable that the ignition system for advanced weapon development consist of a liquid propellant ignited by an energy source already on the self propelled howitzer. This would offer significant

logistical advantages by not introducing additional items into the supply train. Regardless of the composition of the ignition system, a major requirement on performance is that the ignition system ignite a main charge in a prompt, smooth manner and that it do so across a temperature range from -55°C to +65°C.

Two important performance characteristics of the ignition system are peak pressure in the gun chamber and the rise time to that pressure. From past experimental tests, it has been found that the pressure generated in the combustion chamber from the igniter should be in the range of 17 to 21 MPa. The rise time to this pressure is a function of caliber. The rise time should be 1 to 3 ms in a 30-mm and 3 to 5 ms in a large caliber RLPG. In order to examine the performance of the 30-mm RLPG solid propellant igniter, several tests were performed firing the igniter into a closed chamber. Pressures were measured inside the igniter chamber and the closed chamber. The results of a typical test are shown in Figures 2a and 2b. The volume of the igniter chamber is about 7 cm^3 and the volume of the closed chamber is 118 cm^3. The initial chamber volume of the 30-mm RLPG is 95 cm^3, therefore, the peak pressure of 13.1 MPa shown in Figure 2a is slightly lower than would be achieved in the gun fixture. The rise time of 4 ms is close to what is achieved in the gun fixture. The pressure-time curve for the igniter chamber, Figure 2b, can vary depending on the type of igniter used. However, the 155-mm RLPG ignition system must produce a chamber pressure-time curve similar to that illustrated in Figure 2a. The igniter output characteristics shown in Figures 2a and 2b have led to reproducible behavior.

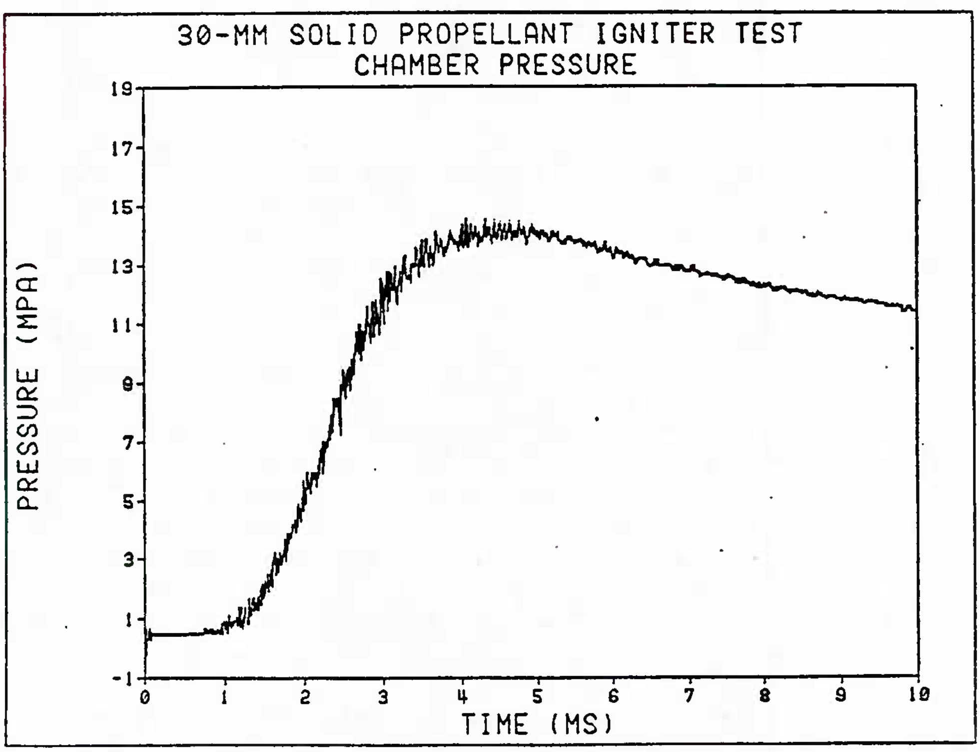

Figure 2(a). <u>30-mm Solid Propellant Igniter Test, Chamber Pressure</u>

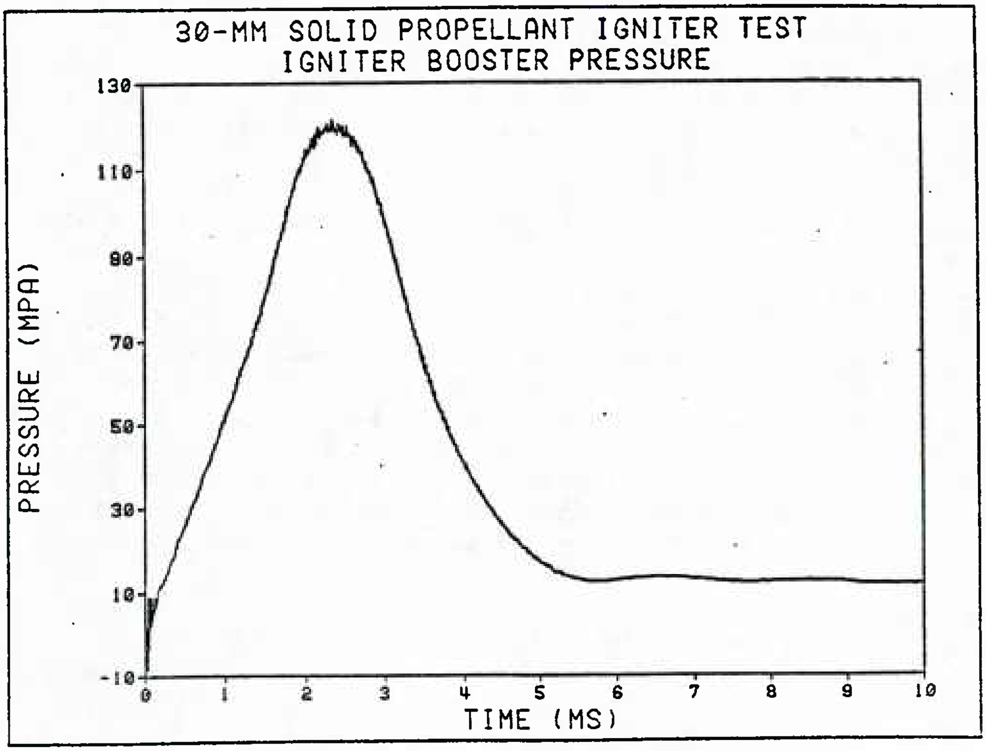

Figure 2(b). <u>30-mm Solid Propellant Igniter Test, Igniter Booster Pressure</u>

Other parameters important to the design of an ignition system are the combustion chamber volume, the initial piston motion, the shot start pressure, and the initial propellant sheet thickness. The combustion chamber volume will determine the amount of igniter charge that is required to attain the specified peak pressure and initial pressure rise rate. The combustion chamber volume for the 155-mm RLPG is expected to be on the order of 6500 cm^3. It has been calculated that a chamber of this size will require up to 250 to 300 grams of liquid propellant to produce the required initial pressure. The initial piston motion could cause a pressure drop in the combustion chamber if the initial chamber volume is too small or if the injected propellant is not immediately ignited. A pressure drop would reduce the effectiveness of the igniter. The projectile shot start pressure can have a similar effect if the projectile starts to move as a result of the igniter pressure. Therefore, it is desirable that the projectile shot start pressure be higher than the pressure produced by the igniter. The thickness of the liquid propellant sheet when it first enters the combustion chamber has a large effect on the efficiency of the ignition system. If this sheet is too thick, the hot gases from the igniter may be quenched from the large amount of propellant entering the combustion chamber and unburned propellant may accumulate in the chamber. The initial sheet thickness

can be adjusted to the needs of the ignition process. However, the lower limit will have to be set by the low temperature operating requirements, due to the increasing viscosity of the LP at low temperatures.

III. IGNITER CONCEPTS

There are two basic igniter concepts being considered. These differ in the location at which the propellant igniter charge is burned, either internal to the gun chamber, or external to the gun chamber. The internal ignition system has the advantage that it will not add a great deal of size to the total gun system since the igniter charge will be burned at a lower pressure inside the gun chamber. The external igniter requires an external precombustion chamber which may increase the size of the total gun system. However, both the internal and the external systems can be designed to integrate efficiently with the gun system.

In an internal igniter, the liquid propellant igniter charge is burned inside the gun combustion chamber. The density of loading for the liquid propellant igniter charge will be about 0.04 g/cm^3 in order to develop the required pressure of 15 to 21 MPa. The advantage of burning the igniter charge inside the combustion chamber is the elimination of a high pressure, external precombustion chamber appended to the gun. However, it is not known at this time whether a sufficiently high mass burning rate of the liquid propellant igniter charge can be achieved at this low loading density.

The external igniter has the advantage that the propellant igniter charge can be burned at a high loading density and thereby obtain a more efficient burning of the liquid propellant. The hot gases produced will then be vented into the combustion chamber, possibly along with some burning propellant, where work can be done on the differential area piston and the liquid propellant charge can be ignited. Another advantage of the external igniter may be a greater control of igniter performance, namely, maximum pressure and pressure rise rate. A disadvantage of the external igniter, since the igniter charge will burn at high pressure, is that the precombustion chamber must be somewhat bulky, adding to the overall size of the breech. Another disadvantage is that the high pressure gases will vent into the gun chamber through a relatively narrow passage, which may be susceptible to a high rate of erosion.

Regardless of the type of ignition system chosen, it is desirable that the ignition energy source be one that is readily available on the self propelled howitzer. The logical choice is to use electrical energy as the initiating source for the igniter. Although there are possibly other methods of ignition, such as laser, acoustic cavitation, or compression ignition, electrical ignition will be given the most attention due both to its promise as an ignition source and its logistical advantage.

1. ELECTRICAL IGNITION

Work was done on igniting liquid propellant charges using an electric discharge in the bulk loaded liquid propellant gun. Work in this area was done by Pulsepower Systems Incorporated (PSI), the Naval Weapons Center (NWC), the Naval Ordnance Station (NOS), and Calspan Corporation. The reader is referred to Reference 2 for a review of the test results on this subject. From the results of this work it was concluded that an electric discharge in a conductive liquid propellant can be broken down into two stages: (1) an ohmic or formative heating which occurs prior to breakdown of the propellant, and (2) an arc or plasma phase operation that occurs after breakdown. The formation of an arc through the liquid is difficult to obtain in highly conductive fluids like the liquid propellants under consideration. More recent studies[5 6] indicate that an alternate mechanism for electrical ignition of the propellant may be electrolysis. The current flow is believed to induce ion migration, which causes an increase in the nitrate ion concentration near the anode. This results in an increase in the nitronium ion concentration at the anode. It is known that the nitronium ion initiates reaction in the propellant and it is believed that this reaction causes a vapor sheath to form around the anode. Then, depending on several factors, an arc may discharge between the anode and the vapor-liquid interface, not between the electrodes.

A type of electrical igniter that may have a potential use as either a bulk loaded or a regenerative igniter is the plasma plug. Research has been done in recent years on the application of pulsed plasma jets for improving ignition and burning rates in the internal combustion engine. This work was done by Weinberg[7] who used hydrogen gas in a modified automobile spark plug. In this modified plug, the center electrode is enclosed in a small chamber with a vent hole. This device operates by discharging a current in the plug. The rapid heating caused by the discharge causes the medium inside the plug to dissociate into free radicals and eject from the plug at high velocity. Recent studies[5 6] have shown that these plasma plugs can be used to ignite HAN based liquid propellants. The amount of propellant used in the plug was on the order of 0.025 cm^3. The ignition characteristics of the plugs fell into two groups. One ignition type, which was usually obtained at the higher capacitor charging voltages, is characterized by a plasma arc discharge which probably formed in an air gap between the electrodes above the propellant. The second type were usually obtained when the charging voltage was relatively low and the plug was filled with propellant or other highly conductive fluid. The first type of ignition led to a plume of hot, reacting propellant venting from the plug. The second type of ignition led to the venting of unburned liquid propellant from the plug followed by burning LP and gases. In this second case the reaction was believed to have started in the vicinity of the center electrode, which was the anode.

Before a plasma plug type igniter can be considered as a component of an ignition system for a 155-mm RLPG, the device must be scaled up in size to make sure the performance characteristics are not size

dependent. This is one objective of the current research effort at the BRL. The igniter currently designed has a nominal propellant capacity of 2 cm^3. This igniter is shown in Figure 3 and represents an increase in propellant volume of eighty times over the amount tested in References 5 and 6. An igniter containing 2 cm^3 of propellant is close to the size needed for a 30-mm RLPG. One goal of the study, therefore, is to test this type of igniter in the 30-mm RLPG at the BRL. The electrical igniter shown in Figure 3 works in a similar fashion as the plasma plug. The maximum pressure obtained in the igniter will be controlled by the area of the venting orifice. The igniter will be vented into a closed chamber and the output pressure will be recorded. The operation of the igniter will be studied at chamber pressures up to 21 MPa, unlike the plasma plugs studied previously[5 6], which were tested at atmospheric pressure only. This design is best suited for a medium caliber RLPG igniter or the first stage of an ignition train for a larger caliber weapon.

There are many parameters of the igniter that will be studied so that optimum performance will be obtained. These parameters include: the polarity of the center electrode; the length of the center electrode; the length of the outer electrode; the size of the venting orifice; and the type of venting orifice. It has been observed that a more vigorous reaction occurs when the center electrode is positively charged. The length of the center and outer electrodes should affect the location of the initial reaction. The size of the venting orifice affects the mass flow rate out of the igniter and hence, the maximum pressure obtained within the igniter. It also affects the rise rate of the pressure in the chamber into which the igniter vents. The type of venting orifice used, single or multi-holes, will affect the way in which the material is vented from the igniter and the size and shape of the venting plume.

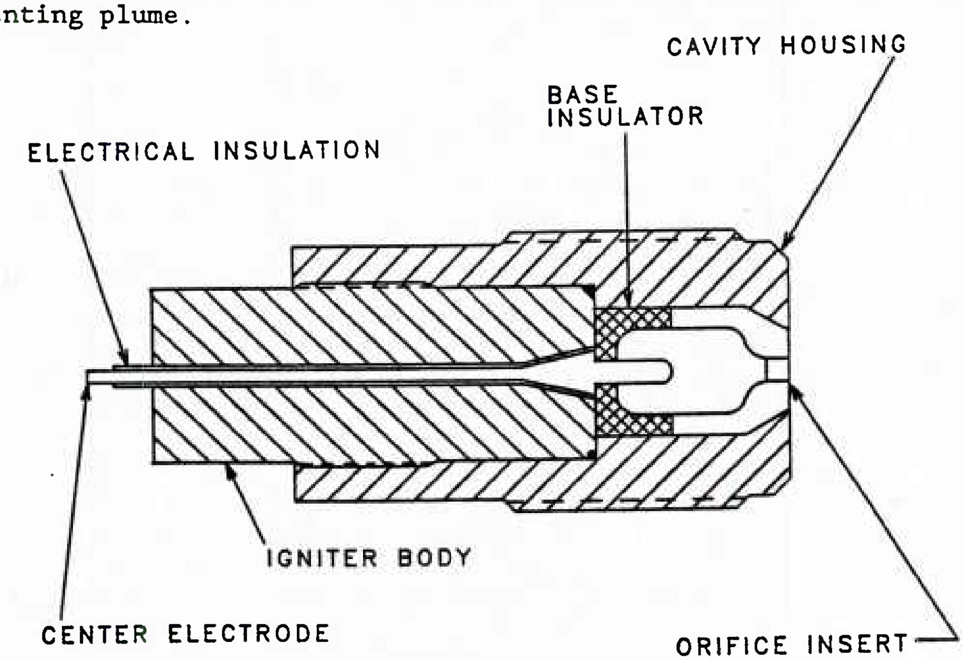

Figure 3. Electrical LP Igniter

2. EXTERNAL IGNITER SYSTEMS

The electrical igniter described above would be an external igniter since it would be located outside the combustion chamber, with the LP cavity serving as the precombustion chamber. With an LP igniter charge volume of 150 to 200 cm^3 for a 155-mm RLPG igniter, the ignition system may resemble an electrically ignited medium caliber bulk loaded LP gun. However, the reproducibility problems that were encountered in the BLPG firings are expected to have less bearing on the ignition system since the generated gas vents into the larger combustion chamber where combustion anomalies would be filtered out. The loading density within the igniter precombustion chamber will be high, therefore there may be efficient propellant burning, especially for small charges. A bulk loaded, external ignition system of this type offers an ignition system which is not excessively complicated.

Another type of external igniter that could be employed in the 155-mm RLPG would be a regeneratively injected igniter charge. The igniter would essentially be a regenerative liquid propellant gun mechanism about the size of a medium caliber RLPG. A small liquid propellant initiator would fire into the precombustion chamber, starting the regenerative pumping of the LP, which would then ignite. The process would be the same as in a medium caliber RLPG firing. However, instead of doing work on a projectile, the burning gases from the ignition in the precombustion chamber would vent into the combustion chamber of the 155-mm RLPG. It is very likely that a system such as this would work since the principles of the regenerative system are well founded. This system would offer effective control of the igniter output which could be achieved by varying both the mass injection rate and the LP igniter charge volume. The primary disadvantages of this system are its bulkiness and its complexity.

3. INTERNAL IGNITER SYSTEMS

In an internal ignition system, the propellant igniter charge is burned inside the combustion chamber of the gun. Using liquid propellant as the igniter charge, there are two configurations that can be employed. Both of these igniter systems entail the burning of the igniter charge at a relatively low loading density of approximately 0.04 g/cm^3. There are issues which must be addressed in order to evaluate these internal systems. These are: (1) the repeatability of the igniter output; (2) the volume of LP which can be ignited in the required time, which is related to; (3) the mass burning rate needed to support the combustion at the low loading density.

The first system is a pool type igniter. In this system, the igniter charge is in the form of a pool in the combustion chamber. A smaller electrical type igniter would be used to ignite the pool. This concept is probably not feasible for the total igniter charge for large caliber RLPGs.

Another internal igniter concept is a spray type igniter. In this system, the LP igniter charge would initially be located in a reservoir, external to the gun chamber. The LP can be injected into the gun chamber by pressurizing a piston with external gas pressure. Another method of injecting LP would be to force early regenerative piston motion in order to generate the spray. After the LP is injected into the chamber in a highly atomized form, an initiator would be fired into the combustion chamber in order to ignite the charge. Some of the LP igniter charge may accumulate in the chamber when it is injected, therefore not all the LP may be in atomized form at ignition. Since the charge will be mostly in the form of droplets, the mass burn rate may be higher than that obtained for the pool type of ignition system, due to the increased propellant surface area.

4. NON-LIQUID PROPELLANT IGNITION SYSTEMS

Ignition systems which use only the liquid propellant itself as the igniter charge are the most desirable because of the logistical advantages. However, two systems that would utilize an igniter charge other than LP were studied. These systems are a hydrogen-air mixture and a fuel-air mixture. These materials could be used in either external or internal ignition systems.

The concept of using a hydrogen and air mixture as an igniter charge for the gun was suggested by A. Birk.[8] This system would operate by pressurizing the combustion chamber of the RLPG with a hydrogen-air mixture. The mixture would then be ignited and would pressurize the combustion chamber and start the RLPG process. A system for storing hydrogen, which was reported to be safe, is a metal hydride system. In this system the hydrogen is stored in a storage unit in solid state using metal hydrides. Metal hydrides are formed when certain metal alloys are exposed to hydrogen gas. These alloys absorb large quantities of hydrogen and form metal hydrogen compounds, where the hydrogen is distributed throughout the metal lattice. Metal hydride storage is said to be safer than compressed gas or liquid hydrogen storage and have higher hydrogen storage capacity.[9] The largest hydrogen storage unit described in Reference 9 has a stored volume of 2,500 liters, a flow rate of 0 to 85 liters per minute, and an output pressure of 0.1 to 2.0 MPa.

A study was performed to determine the feasibility of using such a hydrogen storage system in a hydrogen-air ignition system. The volume of hydrogen that is required for combustion with air to produce a final pressure between 17 and 21 MPa was determined using the NASA-LEWIS thermodynamic code.[10] The amount of hydrogen and air required was then determined for chamber volumes of 50, 500, and 5000 cm^3. The results for a final pressure of 20.4 MPa are summarized in Table 1.

For a combustion chamber volume of 5000 cm^3, 39 liters of hydrogen at STP are required to produce the desired chamber pressure. Based on a stored volume of hydrogen of 2250 liters, each storage unit would contain enough hydrogen for 57 firings before replacement or refilling.

In the same 57 firings, less than 500 liters of liquid propellant would be required for the main charge. Therefore, a hydrogen-air ignition system would occupy four times the volume of the main propellant charge. Another negative factor in this system is the fact that storing hydrogen on the vehicle may increase the vulnerability of the system.

TABLE 1. Required Hydrogen and Air at STP to Give Final Pressure of 20.4 MPa for Three Different Chambers.

Chamber Volume	Pressure initial** total	initial** H_2	final	Required Hydrogen		Required Air		*Number of Firings
cm^3	MPa	MPa	MPa	liter	mole	liter	mole	
50	2.9	0.85	20.4	0.39	0.017	0.92	0.041	5769
500	2.9	0.85	20.4	3.9	0.174	9.2	0.412	576
5000	2.9	0.85	20.4	39.	1.74	92.	4.12	57

* The number of firings listed in the last column is based on an effective stored volume of 2250 liters of hydrogen.

** Column 2 lists the initial total pressure.
Column 3 lists the initial partial pressure for hydrogen.

The calculations also show that 92 liters of air at STP are required for each firing. A calculation was made to determine the power required for operating an air compressor to deliver the required air, assuming 50% compressor efficiency. The calculation was based on an ideal gas and the adiabatic power to generate a required air flow. The air flow required was based on a firing rate of a proposed Advanced field Artillery System 155-mm, which is four rounds in 15 seconds followed by a sustained rate of six rounds per minute. The power calculations were made using the sustained rate of six rounds per minute. A 0.0283 m^3 air storage tank is used in order to accommodate the initial higher firing rates. It was calculated that a 15 to 20 horsepower, multistage compressor would be required under these conditions, which is not unreasonable. It can then be concluded that the required air is not a limiting factor.

The hydrogen-air ignition system has an overall negative impact on the logistics of the gun system because of the number of components needed and the potential for increased vulnerability of hydrogen storage. The fact that space is needed for hydrogen storage units and a multistage compressor, in addition to an electric ignition system, makes this system burdensome.

Another study was performed based on the use of the artillery vehicle fuel and air as an ignition source. In this study, JP4 was selected for convenience in order to make use of data generated in an earlier study.[11] The volume of JP4 required for combustion with air to produce a final pressure of 20.6 MPa was estimated based on the thermochemical calculations summarized in Reference 11. These show that a maximum pressure of 43.6 MPa would be expected from a loading density of 0.05 g/cm^3. Assuming an ideal gas, the loading density required to obtain a pressure of 20.6 MPa was estimated to be 0.0238 g/cm^3. The equivalence ratio for the combustion of JP4 and air, obtained from Reference 12, is 14.78 m_f/m_a, where m_f is the mass of the fuel and m_a is the mass of the air. For stoichiometric combustion, the required volume of air and the volume of JP4 were determined based on the equivalence ratio and the loading density required to yield the desired final pressure of 20.6 MPa. The results are presented in Table 2.

TABLE 2. Initial and Final Conditions for Stoichiometric Combustion of JP4 and Air for Cases Suitable for a RLPG Igniter.

Chamber Volume	Pressure initial	final	Required JP4	Required Air	
cm^3	MPa	MPa	gram	liter	mole
50	1.86	20.6	0.075	0.86	0.0384
500	1.86	20.6	0.753	8.6	0.384
5000	1.86	20.6	7.533	86.	3.84

The calculations show that 86 liters of air at STP is required for combustion with the fuel. This requirement should not pose a problem if analyzed in the same fashion as in the hydrogen-air system. However, the fact that this is a multicomponent system, like the hydrogen-air concept, increases the logistical burdens.

IV. DISCUSSION AND CONCLUSIONS

The four concepts which use the liquid gun propellant as the igniter charge show the greatest potential for use as a 155-mm RLPG ignition system. The bulk loaded external igniter is the least complex, but would entail mounting a bulky precombustion chamber onto the breech of the gun system. The regeneratively injected external igniter has good potential for success, but would add complexity and size to the system. The pool type internal igniter is perhaps the least complex system, however it offers the least control of the ignition process. The spray type igniter, like the pool type igniter, introduces uncertainties about the combustion of the LP at low loading densities.

The latter two concepts will have to be tested in order to evaluate their potential for implementation.

The hydrogen-air and the fuel-air systems are not being tested at the BRL because of the additional components needed in comparison to an all LP ignition system. The hydrogen-air and fuel-air systems require storage of the hydrogen or fuel, a multistage air compressor, a fuel pump or injector, and an electric ignition system. An all LP system would require only the electric ignition system and possibly an injector if the internal, spray igniter was being used. The filling of LP into the igniter could be performed by the main LP charge fill system and, therefore, does not add to the complexity of system.

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